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# An Optically Dark GRB Observed by HETE-2: GRB 051022

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## Abstract

GRB 051022 was detected at 13:07:58 on 22 October 2005 by HETE-2. The location of GRB 051022 was determined immediately by the flight localization system. This burst contains multiple pulses and has a rather long duration of about 190 seconds. The detections of candidate X-ray and radio afterglows were reported, whereas no optical afterglow was found. The optical spectroscopic observations of the host galaxy revealed the redshift z = 0.8. Using the data derived by HETE-2 observation of the prompt emission, we found the absorption $N_{\rm H} = (8.8^{+3.1}_{-2.9}) \times 10^{22}$ cm$^{-2}$ and the visual extinction $A_V = 49^{+17}_{-16}$ mag in the host galaxy. If this is the case, no detection of any optical transient would be quite reasonable. The absorption derived by the Swift XRT observations of the afterglow is fully consistent with those obtained from the early HETE-2 observation of the prompt emission. Our analysis implies an interpretation that the absorbing medium may be outside the external shock at $R \sim 10^{16}$ cm, which could be a dusty molecular cloud.

**Key words:** stars: individual(GRB 051022) — gamma rays: observations — X-rays: ISM

## 1. Introduction

Among gamma-ray bursts (GRBs), "optically dark" bursts are known as GRBs without accompanying optical transients. From lack of a precise location being usually determined by its optical afterglow, it is generally diffi-cult to search out its corresponding host galaxy. Hence there are only a few hosts found to date by radio counter-parts for this kind of bursts, and detailed studies such as their morphology or taxonomy are very premature. Why are these GRBs "optically dark"? The answer is still unclear. Their optical counterparts might have decayed

much rapidly than others, and/or could be hidden behind heavily absorbing matters. Some works suggest that those are associated with dusty molecular clouds along the line of sight (Reichart, Price 2002) or distant GRBs with $z \gtrsim 5$ (Fruchter et al. 1999a; Lamb, Reichart 2000).

In soft X-ray band, measuring the absorptions in spectra of prompt emissions and/or afterglows from GRBs could provide us important information about the environments around sources. Actually some authors reported time-variable absorptions in spectra of some GRB prompt emissions and afterglows. One of the interesting properties of GRB 970828 is a time-variable absorption in the spectra of the afterglow, which could be due to circumburst medium (Yoshida et al. 2001). Similar absorption in the afterglows were also reported by Owens et al. (1998) and Stratta et al. (2004).

For prompt emissions, time-variable absorptions were reported for GRB 980329 (Frontera et al. 2000), GRB 990705 (Amati et al. 2000) and GRB 010222 (in't Zand et al. 2001). Optical counterparts were found for these bursts, in contrast to the case for GRB 970828. Frontera et al. (2000) suggested that a time-variable absorption in the spectra of GRB 980329 was due to the internal shock accompanied by the expanding fireball. For GRB 990705, an absorption feature in the prompt emission might be explained by a photoelectric absorption by a medium at z=0.86 (Amati et al. 2000).

We report here constant absorptions throughout the prompt emission and the afterglow of GRB 051022 observed respectively by HETE-2 and Swift. We also present the localization and the spectral properties of GRB 051022. We discuss output energies of the burst and an evidence for an intervening dense medium along the line of sight.

## 2. Observations and Analyses

### 2.1. Localization

The gamma-ray burst GRB 051022 was detected with the three scientific instruments aboard HETE-2, the Wide-Field X-ray Monitor (WXM; 2-25 keV; Shirasaki et al. 2003), Soft X-ray Camera (SXC; 0.5-10 keV; Villasenor et al. 2003) and French Gamma Telescope (FREGATE: 6-400 keV; Atteia et al. 2003), at 13:07:58 on 22 October 2005 (Graziani 2005; Tanaka et al. 2005). The location of GRB 051022 was determined immediately by the flight WXM and SXC localization system. The GCN Notices reporting the position were sent out 45 seconds after the onset based on the WXM flight localization, and 119 seconds after the onset based on the SXC flight localization.

The WXM location was a circle centered at R.A. = $23^{\rm h}55^{\rm m}55^{\rm s}.2$, decl. = $19°39'36''.0$ (J2000) with a radius of $5'$ (90 % confidence region) by the ground analysis of the data. The brightness of GRB 051022 was sufficient in soft X-rays to determine the position with an error radius down to $1'19''.8$ using the SXC data independently of the WXM localization. Unfortunately the SXC data was partially lost due to the dropout of internet connection to the ground station at Cayenne. The SXC localization was

made by the ground analysis and resulted in a circle centered at R.A. = $23^{\rm h}56^{\rm m}03^{\rm s}.7$, decl. = $19°37'10''.9$ (J2000) ($l = 105°27'20''.0$, $b = -41°21'54''.8$) with a radius of $2'30''$ (90 % confidence region).

The Inter-Planetary Network (IPN) also reported its position (Hurley, Cline 2005) constrained on an annulus centered at R.A. = $03^{\rm h}11^{\rm m}39^{\rm s}$, decl. = $16°32'32''$ (J2000) with a radius of $46.4533 \pm 0.0684$ degrees (the quoted error is $3\sigma$ confidence region). The SXC error circle was just encompassed in this annulus position.

The Swift XRT instrument began observing 3.5 hours after the trigger the field of GRB 051022 based on the HETE-2 localization, and detected a bright unknown fading X-ray source (Racusin et al. 2005a), just $1'6''.8$ away from the center of the SXC error circle. The XRT located it with an accuracy of $4''$ and the Chandra narrowed later its error region down to $0''.7$ (Patel et al. 2005), where the VLA observation at 8.5 GHz discovered a bright radio source (Cameron, Frail 2005). The probable host galaxy was reported by several groups (Castro-Tirado et al. 2005; Berger, Wyatt 2005; Cool 2005; Nysewander et al. 2005; Bloom 2005; de Ugarte Postigo et al. 2005), and the optical spectroscopic observation using the 200-inch Hale Telescope at Palomar Observatory detected a strong line at 6736 Å which corresponds to O II 3727 Å and determined a redshift z = 0.8 (Gal-Yam et al. 2005).

Using the data of Swift XRT instrument, spectral analyses of X-ray afterglow were performed (Butler et al. 2005a, 2005b; Racusin et al. 2005b). Butler et al. (2005a) reported the absorption $N_{\rm H} = (0.84 \pm 0.07) \times 10^{22}$ cm$^{-2}$ which is greater than the Galactic value in the direction to the burst. The light curve of X-ray afterglow presented a break at $t_{\rm break} = 2.9 \pm 0.2$ days, and the jet opening angles were estimated (Racusin et al. 2005b) if this break was due to the sideway expansion; $\theta_{\rm jet} = 4.3$ degrees for the HETE-2 spectral parameters (Doty et al. 2005) and $\theta_{\rm jet} = 4.4$ degrees for the Konus-Wind spectral parameters (Golenetskii et al. 2005).

### 2.2. Temporal Properties

Unfortunately, because of the dropout of internet connection to our ground station at Cayenne at the trigger time, we lost the time tagged photon data of the FREGATE. The spectral and temporal analyses of the FREGATE are performed using the 5.24 s resolution data from this reason. The upper five panels in Figure 1 show the time history of GRB 051022 in five energy bands, where t = 0 shows the trigger time which corresponds to 13:07:58 on 22 October 2005 UT. The event consists of multiple pulses and has a rather long duration $T_{90} = 178 \pm 8$ s in the $2-25$ keV energy band and $157 \pm 5$ s in the $30-400$ keV energy band.

### 2.3. Absorption in Spectra

In our analysis, we use the following models: power-law (PL), power-law times exponential cutoff (PLE) and Band function (GRBM; Band et al. 1993). The WXM and the FREGATE were pointed to around R.A. = $01^{\rm h}08^{\rm m}00^{\rm s}$, decl. = $11°08'00''$ (J2000) ($l = 129°28'14''.0$,

$b = -51°31'40''.9$) when the GRB was observed. The FREGATE has larger field-of-view of 70 degrees than that of the WXM, and we found many mildly bright soft sources at that time within the FREGATE field-of-view but outside the WXM consulting the ASM/RXTE database. The spectrum of FREGATE shows somewhat larger counts near its lower energy end than those from the WXM in the same band. This could be due to contamination from the soft sources mentioned above. To avoid this discrepancy only in the lower end of energy band of the FREGATE, we employ data above 40 keV up to 400 keV for joint fits and find very good agreement in continuum spectra with the WXM and the FREGATE.

First of all, we analyze the average spectrum of the prompt emission using the total duration t $= 21-220$ s. For background we employ data during t $= 231-341$ s. Their time regions are indicated in Figure 1. Any unabsorbed model does not provide an acceptable fit to the data. We find a deficit of photons in the spectrum using unabsorbed GRBM model in lower energy band below 4 keV (see panel (b) of Figure 2). The Galactic value of absorption in the direction of the burst is $4.09 \times 10^{20}$ cm$^{-2}$ (Dickey, Lockman 1990), which is negligible for this fit. Then, we adopt an absorption as a free parameter and fit the data. The fit is clearly improved (see panel (c) of Figure 2) and the most favorable model is the absorbed GRBM with $N_{\rm H} = (1.51^{+0.53}_{-0.50}) \times 10^{22}$ cm$^{-2}$. Using the absorbed GRBM model, we find $\alpha = 1.01^{+0.02}_{-0.03}$, $\beta = 1.95^{+0.25}_{-0.14}$, $E_{\rm peak}^{\rm obs} = 213 \pm 18$ keV, and fluences $S_{\rm X} = (21.4 \pm 0.2) \times 10^{-6}$ ergs cm$^{-2}$ (2$-$30 keV) and $S_\gamma = (131 \pm 1) \times 10^{-6}$ ergs cm$^{-2}$ (30$-$400 keV). The quoted errors correspond to the 90 % confidence region for $N_{\rm H}$, $\alpha$, $\beta$ and $E_{\rm peak}^{\rm obs}$, and the 68 % confidence region for $S_{\rm X}$ and $S_\gamma$. Thus the ratio of fluences is $\log(S_{\rm X}/S_\gamma) = -0.786$, and GRB 051022 is classified into the "Classical" hard GRB in the HETE-2 sample (Sakamoto et al. 2005).

In previous studies for GRBs, the absorption appeared only in a part of a prompt emission and/or afterglow (Amati et al. 2000; Frontera et al. 2000; in't Zand et al. 2001; Yoshida et al. 2001; Stratta et al. 2004). Then we perform the time resolved spectral analyses for 10 time intervals to investigate a time variation of the absorption, and summarize the results in Table 1. The bottom three panels in Figure 1 show the time variation of these spectral parameters. In all time intervals, we adopt the absorbed PLE model because reliable $\beta$ cannot be obtained from these fittings with GRBM model. The quoted errors correspond to the 90 % confidence region for $N_{\rm H}$, $\alpha$ and $E_{\rm peak}^{\rm obs}$, and the 68 % confidence region for $S_{\rm X}$ and $S_\gamma$.

From the spectral variation, the initial pulse (t $= 21.0-36.7$ s) is hard and accompanied by a soft pulse (t $= 36.7-57.7$ s). During the later long phase (t $= 57.7-220$ s), the spectrum shows a softening trend. These are consistent with the general view of the time variation of GRB spectra. The most remarkable result is that $N_{\rm H}$ is significantly needed and seems constant in all the time intervals contrary to the results from the previous studies. Then we perform spectral fitting by assuming the absorption fixed to the value obtained by the analysis of the average spectrum and get acceptable fits for all intervals (see $\chi'^2$ in Table 1). In conclusion, $N_{\rm H}$ does not seem to have a significant evolution.

## 3. Discussion and Conclusion

Using the measured redshift $z = 0.8$ (Gal-Yam et al. 2005), the luminosity distance is given by $d_{\rm L} = 1.49 \times 10^{28}$ cm ($\Omega_m = 0.32$, $\Omega_\Lambda = 0.68$ and $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$). $E_{\rm iso}$ turns out to be $(6.6 \pm 1.3) \times 10^{53}$ ergs by integrating the best-fit time integrated spectrum in the observer frame over the energy ranging from $1/(1+z)$ keV to $10/(1+z)$ MeV (Bloom et al. 2001, 2003; Amati et al. 2002). We also find the peak energy of $\nu F_\nu$ spectrum in the source frame $E_{\rm peak}^{\rm src} = 382^{+33}_{-32}$ keV. These values are lying on $E_{\rm peak}^{\rm src} - E_{\rm iso}$ relation (Amati et al. 2002).

In the standard view, the fireball is collimated (Waxman et al. 1998; Fruchter et al. 1999b) and the collimation corrected energies are concentrated around $10^{51}$ ergs (Bloom et al. 2003; Ghirlanda et al. 2004). This scenario is believed to appear as the achromatic break in observed afterglow light curve (Rhoads 1997; Sari et al. 1999). The break time of the light curve $t_{\rm break} = 2.9 \pm 0.2$ days was reported using the X-ray afterglow observations (Racusin et al. 2005b). If this is due to the jet break, the jet opening angle $\theta_{\rm jet}$ (Sari et al. 1999) turns out to be $\sim 4.2$ deg assuming $n \sim 0.1$ cm$^{-3}$ and $\eta_\gamma \sim 0.2$, where $n$ is a proton number density around the GRB site and $\eta_\gamma$ is an energy conversion efficiency. Then, we estimate the collimation corrected energy $E_\gamma$ (Bloom et al. 2003; Ghirlanda et al. 2004) scaling $E_{\rm iso}$ by $(1-\cos\theta_{\rm jet})$ and find $E_\gamma = (1.8 \pm 0.3) \times 10^{51}$ ergs. This value is lying on $E_{\rm peak}^{\rm src} - E_\gamma$ relation (Ghirlanda et al. 2004). Thus the jet break at 2.9 days seems plausible.

The follow-up observations of X-ray afterglow were performed by the Swift XRT instrument from 16:35:54 on 22 October 2005 (Racusin et al. 2005a). Using the three orbits of XRT data, we performed spectral analyses of the afterglow, and found $N_{\rm H} = (0.91^{+0.12}_{-0.11}) \times 10^{22}$ cm$^{-2}$ and $\Gamma = 2.0 \pm 0.1$ with $\chi^2/{\rm d.o.f.} = 166/150$. These values are consistent with that previously reported by Butler et al. (2005a). We also found a constant absorption during the XRT observation. The absorption derived by the Swift XRT observation is fully consistent with those obtained from the early HETE-2 observation of the prompt emission. In earlier studies, it was reported that the absorption varied in time (Amati et al. 2000; Frontera et al. 2000; in't Zand et al. 2001; Yoshida et al. 2001; Stratta et al. 2004) and therefore it was interpreted as an absorption by the circum-burst dusty medium in the very vicinity of internal shocks. In contrast, our analyses present the constant absorption throughout the prompt emission and the afterglow. It might be due to the intervening medium along the line of sight which is in the outside of external shocks; i.e. a molecular cloud in the host galaxy.

The large absorption would cause the extinctions of the afterglow emission. If the intervening medium is located somewhere in the middle between the source and

our galaxy, the absorption should be at least $N_H \gtrsim (1.51^{+0.53}_{-0.50}) \times 10^{22}$ cm$^{-2}$. We find the visual extinction at minimum $A_V = 8.4^{+3.0}_{-2.8}$ mag using the relationship $A_V = N_H/(1.79 \times 10^{21}$ cm$^{-2})$ found by Cardelli et al. (1989). Then we estimate the extinctions for other wavelengths at minimum using the extinction curves found by Predehl, Schmitt (1995); $A_U = 13.2^{+4.7}_{-4.4}$ mag, $A_B = 11.3^{+4.0}_{-3.7}$ mag, $A_R = 6.3^{+2.2}_{-2.1}$ mag, $A_I = 4.0^{+1.4}_{-1.3}$ mag, $A_J = 2.4 \pm 0.8$ mag, $A_H = 1.6^{+0.6}_{-0.5}$ mag, $A_K = 1.0 \pm 0.3$ mag and $A_L = 0.5 \pm 0.2$ mag. These large extinctions could explain the fact that no optical afterglow was found despite the prompt and deep search (Torii 2005; Cenko et al. 2005).

The most extreme case is that the intervening medium is located in the very vicinity of the host galaxy of GRB 051022. The absorption should be scaled by $(1+z)^3$ (Gunn, Peterson 1965). We find $N_H = (8.8^{+3.1}_{-2.9}) \times 10^{22}$ cm$^{-2}$ and the extinctions are $A_V = 49^{+17}_{-16}$ mag, $A_U = 77^{+27}_{-25}$ mag, $A_B = 66^{+23}_{-22}$ mag, $A_R = 37^{+13}_{-12}$ mag, $A_I = 24 \pm 8$ mag, $A_J = 14 \pm 5$ mag, $A_H = 9 \pm 3$ mag, $A_K = 6 \pm 2$ mag and $A_L = 3 \pm 1$ mag at maximum. If this is the case, no detection of any optical transient would be quite reasonable.

Considering that no optical afterglow is found despite a prompt deep search of afterglow down to $R \sim 20.0$ mag (Cenko et al. 2005), GRB 051022 is very similar to GRB 970828 which is one of the important GRBs for which no optical afterglow was found despite a prompt deep search down to $R \sim 24.5$ mag (Odewahn et al. 1997). Djorgovski et al. (2001) reports that the radio afterglow of GRB 970828 is located between two bright sources (A and B in Figure 3 of Djorgovski et al. 2001). They suggest that there might be a dust lane intersecting a single galaxy or it might be a merging system of three components (A, B and C in Figure 3 of Djorgovski et al. 2001). The star formation rates (SFR) are reported by the authors as SFR$\sim$1.2 $M_\odot$ yr$^{-1}$ for component A and SFR$\sim$0.3 $M_\odot$ yr$^{-1}$ for B.

The absorption for GRB 970828 using the brightness of X-ray and radio afterglow was $N_H \gtrsim 6 \times 10^{21}$ cm$^{-2}$ in the source frame, therefore a dusty molecular cloud is one possible interpretation (Djorgovski et al. 2001). Meantime Yoshida et al. (2001) shows a time-variable absorption with $N_H = 3.13 \times 10^{22}$ cm$^{-2}$ in the source frame based on the spectral analyses of the X-ray afterglow. Therefore the most probable interpretation is that the absorption could be dominantly due to the medium near the GRB site (Yoshida et al. 2001; Djorgovski et al. 2001).

For GRB 051022, several authors report, based on the optical and IR observations, the most probable candidate of its host galaxy (Castro-Tirado et al. 2005; Berger, Wyatt 2005; Cool 2005; Nysewander et al. 2005; Bloom 2005; Gal-Yam et al. 2005; de Ugarte Postigo et al. 2005) at the location consistent with those of the burst (SXC), the X-ray afterglow (XRT), and the radio transient (VLA). From these images, the host galaxy (i.e., galaxy "B" in the above references) seems roundly extended at least $\sim 1''$ in radius, which corresponds to be about 7 kpc at $z = 0.8$, greater than the typical size of a galactic bulge. Therefore it would not be an "edge-on" spiral galaxy.

There is also a report that this galaxy is blue with SFR

of more than 20 $M_\odot$ yr$^{-1}$ (Castro-Tirado et al. 2006). The value is far larger than that for GRB 970828. This large SFR could be consistent with a dusty molecular cloud in the galaxy. In addition, GRB 051022 shows the constant absorption in the soft X-ray band throughout the prompt emission and the afterglow. This sharply contrasts with the previous results (Amati et al. 2000; Frontera et al. 2000; in't Zand et al. 2001; Yoshida et al. 2001; Stratta et al. 2004). The absorption for GRB 051022 is evaluated to be $N_H = (8.8^{+3.1}_{-2.9}) \times 10^{22}$ cm$^{-2}$, which is larger than that of GRB 970828. Our results favor an interpretation that the absorbing medium is outside the external shock at $R \gtrsim 10^{16}$ cm and could be a dusty molecular cloud.

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**Table 1.** Spectral model parameters for the time resolved spectra of GRB 051022.

| Time Region (s) | $N_{\rm H}$ [*] | $\alpha$ | $E_{\rm peak}^{\rm obs}$ [†] (keV) | $S_{\rm X}$ [‡] | $S_\gamma$ [‡] | $\chi^2$ (d.o.f.) | $\chi'^2$ [§] (d.o.f.) |
|---|---|---|---|---|---|---|---|
| 21.0-36.7 | $2.7^{+2.7}_{-2.0}$ | $0.81^{+0.07}_{-0.07}$ | $210^{+30}_{-23}$ | $1.32^{+0.06}_{-0.04}$ | $10.8^{+0.2}_{-0.3}$ | 79.1 (106) | 80.0 (107) |
| 36.7-57.7 | $7.1^{+8.8}_{-5.0}$ | $1.16^{+0.23}_{-0.23}$ | $101^{+60}_{-25}$ | $0.61^{+0.03}_{-0.05}$ | $1.8^{+0.1}_{-0.4}$ | 52.6 (57) | 56.2 (58) |
| 57.7-105 | $1.5^{+1.1}_{-1.0}$ | $0.93^{+0.04}_{-0.04}$ | $248^{+26}_{-21}$ | $4.34^{+0.09}_{-0.07}$ | $32.8^{+0.6}_{-0.6}$ | 82.2 (106) | 82.2 (107) |
| 105-121 | $2.6^{+1.3}_{-1.1}$ | $0.77^{+0.03}_{-0.03}$ | $352^{+29}_{-25}$ | $3.27^{+0.05}_{-0.06}$ | $41.1^{+0.4}_{-0.5}$ | 99.1 (106) | 102 (107) |
| 121-131 | $1.4^{+1.0}_{-0.9}$ | $1.05^{+0.05}_{-0.05}$ | $195^{+29}_{-22}$ | $1.68^{+0.04}_{-0.04}$ | $8.8^{+0.2}_{-0.3}$ | 83.4 (106) | 83.4 (107) |
| 131-142 | $3.0^{+1.7}_{-1.4}$ | $1.02^{+0.06}_{-0.06}$ | $226^{+40}_{-30}$ | $1.60^{+0.03}_{-0.04}$ | $9.9^{+0.2}_{-0.3}$ | 87.2 (106) | 90.4 (107) |
| 142-157 | $1.1^{+0.9}_{-0.8}$ | $0.98^{+0.05}_{-0.05}$ | $132^{+12}_{-10}$ | $2.37^{+0.05}_{-0.04}$ | $9.9^{+0.2}_{-0.4}$ | 65.9 (106) | 66.6 (107) |
| 157-168 | $1.9^{+1.1}_{-1.0}$ | $1.17^{+0.06}_{-0.06}$ | $165^{+34}_{-24}$ | $1.58^{+0.04}_{-0.03}$ | $6.2^{+0.2}_{-0.3}$ | 61.4 (88) | 61.8 (89) |
| 168-205 | $1.0^{+0.8}_{-0.7}$ | $1.21^{+0.06}_{-0.07}$ | $100^{+15}_{-11}$ | $3.23^{+0.05}_{-0.07}$ | $8.1^{+0.2}_{-0.3}$ | 78.4 (106) | 79.7 (107) |
| 205-220 | $1.7^{+1.4}_{-1.2}$ | $1.39^{+0.11}_{-0.11}$ | $100^{+42}_{-21}$ | $1.18^{+0.03}_{-0.05}$ | $2.5^{+0.1}_{-0.3}$ | 82.1 (90) | 82.2 (91) |

[*] $N_{\rm H}$ denotes the photoelectric absorption in units of $10^{22}$ cm$^{-2}$ with 90 % confidence level errors.
[†] $E_{\rm peak}^{\rm obs}$ denotes the peak energy of $\nu F_\nu$ spectrum in observer frame with 90 % confidence level errors.
[‡] $S_{\rm X}$ and $S_\gamma$ denote the fluences in the energy range $2-30$ keV and $30-400$ keV respectively, in units of $10^{-6}$ ergs cm$^{-2}$ with 68 % confidence level errors.
[§] $\chi'^2$ denotes the chi-square of the fits, assuming the absorption fixed to the value obtained by the analysis of the average spectra.
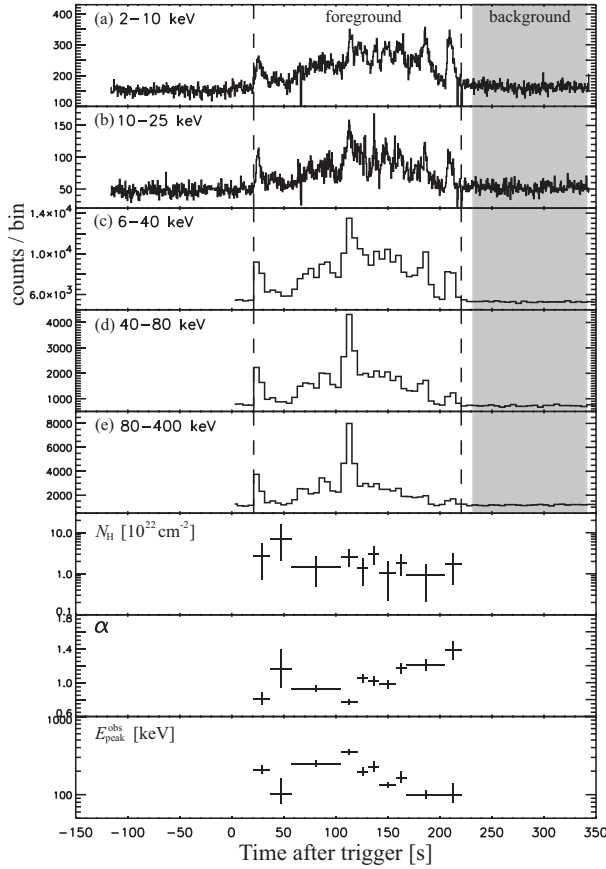


**Fig. 1.** Time history (counts/bin) of GRB 051022 observed by the WXM in the 2-10 keV energy band (a) and the 10-25 keV energy band (b) with 0.5 s time bins; and by the FREGATE in the 6-40 keV energy band (c), the 40-80 keV energy band (d) and the 80-400 keV energy band (e) with 5.24 s time bins. The dashed lines show the foreground region and the hatched area displays the background region. The bottom three panels show the variation of spectral parameters. The quoted errors correspond to the 90 % confidence region.
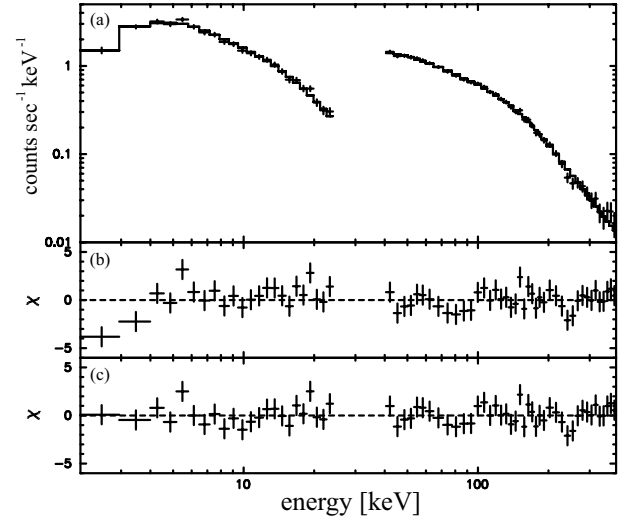


**Fig. 2.** The average spectra with the best-fit absorbed GRBM model (a), the residual using the unabsorbed GRBM model (b) and the residual using the absorbed GRBM model (c).

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